DEVELOPING HYBRID OPTIMIZATION APPROACH FOR MINIMIZING TRAIN SCHEDULING DELAYS IN INDIAN RAILWAYS

SHORT SYNOPSIS

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Certificate

I hereby declare that the Short Synopsis titled "Developing Hybrid Optimization Approach for Minimizing Train Scheduling Delays in Indian Railways" being submitted in partial fulfilment of the requirement for the degree of Doctor of Philosophy in the Department of Computer Science and Engineering under the School of Engineering and Technology of Manav Rachna International Institute of Research & Studies, Faridabad during the academic year 2024. It is a bona fide record of original work carried out under the supervision of Dr. Ramesh Chandra Sahoo & Dr. Prashant Dixit. It has not been submitted in full or part to any other university or institute for a degree or diploma. Further, it is certified that Short Synopsis is plagiarism-free, and proof has been submitted.

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Abstract

An essential part of India's transportation infrastructure, Indian Railways, the country's fourth-largest railway network worldwide, promotes mass mobility, socio-economic development, and connectivity. It began as a 34-kilometer trip between Bori Bunder, Bombay and Thane in 1853, powered by three locomotives: Sindh, Sahib, and Sultan. Across 7,349 railway stations, Indian Railways currently runs approximately 22,593 trains that carry 24 million passengers and 203 million tonnes of freight per day. Even while IR brought in ₹2.39 Lakh Crore in income in FY 2022–2023, it still has a lot of issues in the current world, especially when it comes to train punctuality, which is a crucial indicator of operational effectiveness and passenger happiness. Train punctuality was 94.17% in FY 2020–21 and dropped to 90.48% in FY 2021–22, indicating the need for more concentrated efforts in this area.

Numerous factors, such as network congestion, inadequate infrastructure, weather, and rising demand for passenger and freight services, have an impact on the railway system's punctuality. There are two types of delays that have a major impact on punctuality; primary delays and secondary delays. Direct causes like weather conditions, operational difficulties, or typical events like fires or accidents are the main causes of primary delays. As railway operations are interrelated and one delayed train can impact the scheduling of other trains, secondary delays arise as a result of primary delays.

Optimization techniques like Hungarian Algorithm, Two Phase Approach (TPA) Method, Jonker-Volganant Algorithm, First In First Out (FIFO) Algorithm, Linear Programming and Hybrid Approaches, etc are essential to increase productivity and decrease delays. Applications in engineering, finance, and operations, optimization is the process of determining the best way to solve a problem while meeting a set of constraints. By putting these strategies into practice, Indian Railways might improve operations and may improve the punctuality of trains, efficient use of infrastructure, meet the demands of its extensive passenger and freight network more effectively, and improve punctuality while cutting costs.

Keywords: Assignment Problem, Delay, Indian Railways, Optimization Techniques, Train Punctuality, Train Scheduling.

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1 DESCRIPTION OF BROAD AREA

1.1 INDIAN RAILWAYS

The Indian Railways (IR) operates the world's fourth-largest train network. It is vital for facilitating mass transit, connecting distant places, and contributing significantly to the country's socioeconomic development. IR was established in 1853. The first train traveled from Bori Bunder, Bombay to Thane, a distance of 34 kilometers. On April 16, 1853, it was powered by three locomotives named Sahib, Sultan, and Sindh, with thirteen cars. The Indian Railways operates 22,593 trains/day, carrying 24 million passengers and 203 million tons of freight. 7,349 railway stations operate under the authority of 70 railway divisions, with each station operating independently for train operations. In FY 2022-2023, the total expenditure and revenue were ₹2.37 and ₹2.39 lakh crore, respectively [28], [29]. The railway network, which serves as the backbone of India's transportation infrastructure, faces various issues today. Timely departures, effective station operations, and optimal resource utilization are essential elements that directly affect operational success and customer satisfaction.

1.2 TRAIN PUNCTUALITY

According to Indian Railways Annual Report & Accounts 2020-21 & 2021-22 [28], [29], train punctuality for the FY 2020-21 and FY 2021-22 was 94.17% and 90.48%, respectively. These figures are incredibly high and demonstrate Indian Railways' great priority for punctuality. In every railway system, there has been debate and worry about train punctuality. The ability of trains to arrive and depart on time is referred to as punctuality. The main elements influencing the railway system's punctuality include traffic management, increasing passenger and freight demands, weather, infrastructure problems, network congestion, and operational challenges [30].

1.3 CLASSIFICATION OF DELAY FACTORS IN RAILWAYS SYSTEM

A train is considered to be delayed when it departs from its starting point, travels later than planned, and arrives at its destination station later than expected. Any railway system's classification of delays is divided into various subcategories, although they can be essentially divided into two categories: primary delays and secondary delays.

1.3.1 Primary Delays

The term "primary delay" in railways refers to the initial delay caused by a variety of factors that impact a train's scheduled travel. These delays are the direct result of disturbances or issues that prohibit the train from departing or arriving on schedule. Some common reasons of main delays are:

- **Unusual Occurrence**: Cattle run over, accident, Fire, etc.
- **Environment factors**: Heavy Rain, Wind, Snow, Flood, Landslide, Earthquake, etc.
- **Operational Causes**: Crew issues, Vehicle Problems, Unscheduled maintenance due to failure, etc.
- **External Factors**: Obstruction of the track, Passenger issues, etc.

1.3.2 Secondary Delay

Secondary delays in railways arise as a result of main delays, in which one train's delay creates subsequent delays for other trains. These delays occur because railway operations are interrelated, with train movement and scheduling being interdependent. The following are some common causes of secondary delays:

- **Track Occupancy**: A delayed train occupying a section of track or a platform longer than scheduled can prevent other trains from accessing the same track or platform, causing them to wait.
- **Connection Delays**: Trains scheduled to connect with the delayed train must wait for its arrival to ensure passengers can transfer, leading to a cascade of delays.
- **Arrival and Departure Delay (Scheduling Conflicts)**: The initial delay disrupts the planned schedule, leading to a domino effect where subsequent trains cannot adhere to their allocated time slots.

1.4 OPTIMIZATION TECHNIQUES

Optimization problems focus on determining the ideal value of an objective function while satisfying a set of predefined constraints. The objective function mathematically represents the goal of the optimization—whether it involves minimizing costs, maximizing efficiency, or enhancing performance. On the other hand, constraints define the requirements that must be met for the solution to be

considered valid. Optimization techniques are widely applicable across various fields, including computer science, engineering, and finance. They play a critical role in industries by helping solve complex problems, maximize resource usage, and drive significant improvements in operations. These techniques can be applied to minimize production costs, optimize workflow processes, improve revenue generation, and ensure efficient time management. As a result, businesses can leverage optimization algorithms to improve decision-making and increase overall productivity.

- Finding the optimal value for an objective function that fulfills a given set of restraints is the focus of optimization problems.
- The constraints are the requirements that the solution must meet, while the objective function is the function that is being optimized.
- Engineering, finance, computer science, and many other disciplines are just a few examples of the various disciplines where optimization algorithms can be applied.
- They can be used to find solutions for cutting production costs, increasing revenues, speeding up work completion, efficient use of time and many more.

A specific type of optimization problem is the assignment problem, which is highly beneficial in areas like train scheduling. The assignment problem involves allocating a set of tasks to a set of resources in the most efficient manner possible. For instance, in train scheduling, the problem can be used to allocate trains to specific routes, tracks, or time slots. This ensures that the scheduling of trains is done optimally, minimizing costs, delays, or idle time while maximizing the efficient use of resources such as tracks and locomotives. The assignment problem can be formulated as a linear programming problem, where the goal is to determine the most optimal allocation of resources to tasks based on a given objective, such as minimizing costs or maximizing benefits. In the assignment problem, each agent (train) can only be assigned to one task (route or time slot), and each task can only be assigned to one agent. The aim is to find the assignment that best aligns agents with tasks while adhering to the cost or benefit function. Mathematically, this can be expressed using a bipartite graph, with two sets of nodes representing agents and tasks, respectively. The edges between the nodes signify the possible assignments, and each edge has an associated weight that represents the cost or benefit of that assignment. The goal is to find the optimal

matching, where every agent is assigned to exactly one task, and the total cost is minimized, or the total benefit is maximized. Various algorithms have been developed to solve the assignment problem efficiently. One of the most well-known is the Hungarian algorithm [6], which is widely used due to its effectiveness in finding optimal assignments. Other notable algorithms include the shortest path augmenting path algorithm, the Auction Method [38], and the Jonker-Volgenant algorithm [37], each offering different approaches to solve the problem under varying conditions. The assignment problem is applicable in many domains, from logistics and manufacturing to scheduling and resource allocation. For example, in logistics, it can be used to assign delivery vehicles to routes in a way that minimizes travel time or fuel consumption. In manufacturing, it helps assign tasks to machines to reduce production costs or completion time. In scheduling, it ensures that shifts are assigned to employees in a way that guarantees adequate coverage while minimizing labor costs. By addressing these complex scenarios, the assignment problem offers a powerful tool for optimizing decisions across a wide array of industries.

Over the recent years, to solve assignment problems sufficiently; Humayra Dil Afroz & Jyoti Das [1] proposed the basic structure of the Hungarian Algorithm but introduced specific modifications at each step. The steps involve adjusting the cost matrix, normalizing rows and columns, making assignments, checking optimality through line drawing, and iteratively refining the solution until an optimal assignment is achieved. This type of approach falls under the broader category of combinatorial optimization algorithms, and more specifically, it addresses the assignment problem. Farzana Afrin Min et al [3] proposed an approach that follows a heuristic method known as the ‘Assignment by Adjustment’ or ‘Row Minima Method’ for solving the assignment problem. The assignment problem involves finding the most cost-effective way to assign a set of jobs to a set of machines, workers, or resources. This approach is a heuristic because it relies on a simple and fast procedure for finding an assignment, but it does not guarantee optimality. It provides a feasible solution quickly, but the solution may not be the most cost-effective in all cases. R. Murugesan & T. Esakkiammal [22] proposed approach is a step-by-step process for solving an Assignment Problem, a type of combinatorial optimization problem. This method involves balancing the assignment table, constructing the Matrix of Opportunity Costs (MOC), making assignments, and iterating until all assignments are made. This

approach follows a systematic procedure to find an optimal solution to an Assignment Problem, considering balancing, opportunity costs, and tie-breaking techniques. V. Meczko et al [2] proposed approach described involves using the Excel Solver for optimization, specifically for solving an operator-machine assignment problem. This is an example of a mathematical programming approach, specifically linear programming, where the goal is to optimize a linear objective function subject to certain linear constraints. Neha Rai et al [12], Humayra Dil Afroz et al [11] proposed approach is a heuristic method because it involves making decisions based on local information (e.g., considering the current row's zeros) rather than exhaustively exploring all possible assignments. It might not guarantee the globally optimal solution, but it provides a reasonable solution in a more computationally efficient manner. This algorithm seems similar to some heuristics used in solving the Assignment Problem, and it falls under the category of constructive heuristics. Constructive heuristics build a solution step by step, making locally optimal decisions at each stage.

2 LITERATURE REVIEW

The assignment problem is a classic optimization scenario in operations research and combinatorial optimization. It involves finding the most cost-effective assignment of a set of tasks to a set of resources. This problem arises in various real-world applications such as workforce management, project scheduling, and transportation planning. In its simplest form, the assignment problem can be framed as follows: Given a set of tasks and a set of resources, each with associated costs or weights, the goal is to find the optimal assignment that minimizes the total cost. The problem is often represented as a cost matrix, where each element represents the cost of assigning a particular task to a specific resource. Various approaches have been created over time to address this issue, each with its own set of strengths and weaknesses. Some are as follows:

2.1 HUNGARIAN METHOD

The Hungarian method, introduced by Kuhn in 1955 [6], is one of the most popular methods for addressing the assignment problem. It effectively determines the optimal solution in polynomial time, making it appropriate for small to medium-sized problems. The Hungarian technique divides the problem into a succession of simpler sub-problems by combining matrix reduction and augmenting routes, eventually leading to the optimal assignment. While incredibly efficient, it may face scaling challenges with huge problem instances.

2.2 LINEAR PROGRAMMING

Linear programming (LP) techniques can be used to solve the assignment problem by transforming it into an LP problem and employing optimization solvers. LP-based techniques provide flexibility in dealing with various sorts of cost matrices and limitations. They can provide optimal answers and handle increasingly complex variations of the assignment problem. However, solving large-scale LPs can be computationally demanding and may not be as efficient as specialized assignment techniques for smaller instances [9].

2.3 NETWORK FLOW ALGORITHMS

Network flow algorithms, such as the minimum cost flow algorithm, can be used to solve the assignment problem by representing it as a flow network. While capable of discovering optimal solutions, some methods may be more sophisticated than other algorithms. Network flow techniques are very useful when dealing with extra limitations or expanding the assignment problem to more complex circumstances [14].

2.4 HEURISTIC AND GREEDY METHODS

Heuristic methods, such as the "row and column scanning" approach, offer quickly and approximate answers to the assignment problem. These methods are useful for creating initial solutions, particularly in larger scenarios where optimality is harder to achieve. Greedy algorithms that iteratively make locally optimum assignments can yield good answers, but may not ensure global optimality [15].

2.5 BRANCH AND BOUND

The branch and bind technique investigate the solution space by recursively splitting it into smaller sub-problems and restricting the search to find the best assignment. While it ensures optimality, its effectiveness is dependent on the branching strategy and the quality of the bounding approaches. It can be effective in circumstances where optimality is critical and other methods may fall short [3].

2.6 METAHEURISTIC ALGORITHMS

Metaheuristic techniques, such as genetic algorithms, simulated annealing, and particle swarm optimization, provide a balance between solution quality and computing time. These techniques are valuable in difficult assignment situations where typical methods may fail. However, their convergence to optimal solutions is not assured and fine-tuning is frequently required [17], [25], [31].

2.7 HYBRID APPROACHES

Hybrid methods incorporate aspects from many techniques to maximize their strengths. For example, combining the Hungarian technique with local search strategies can boost solution quality and efficiency. These approaches seek to

capitalize on the advantages of various methodologies while limiting their downsides [16].

Finally, there are several approaches for handling the assignment problem, each with pros and disadvantages. The approach chosen is determined by several parameters, including issue size, cost matrix structure, available computer resources, and the desired balance of solution quality and calculation time. Researchers continue to develop hybrid approaches and apply improved optimization techniques to effectively handle larger and more complicated assignment situations. To solve the real life assignment problems, in recent years, many efforts are made with discrete type of assignment problems.

Yani Iriania and Tendy Andrian [23] introduce the use of the Hungarian assignment method to optimize employee assignments in the sewing line area to address the issue of delays in work completion and increased overtime due to the company's current assignment practices, resulting in a significant reduction in work completion time from 43.3 hours to 35 hours.

Zsolt Ercsey and Zoltán Kovács [18] address the problem of allocating work assignments to employees within a given time horizon, considering varying manpower demands and compliance with labor standards and regulations, formulate a corresponding Mixed Integer Linear Programming (MILP) mathematical programming model in a simple scenario where there is only one position for labor, as well as in a general case where there are multiple positions with different skill requirements, The models offer a fast and effective method for human resource managers to optimize labor scheduling and support decision-making in workforce allocation.

Trupti A Thakre et al [26] explore how fuzzy assignment problems address the limitations of classical approaches, offering a solution for the placement of candidates across different designations in the Life Insurance Corporation sector, employing various methodologies for comparison and analysis. The utilization of the magnitude ranking method and various solution techniques like the Hungarian method, Matrix One's assignment method, and direct method for the fuzzy assignment problem

highlights its effectiveness in efficiently placing candidates for different posts in the Life Insurance Corporation, ensuring optimal placements with consistent outcomes.

Akinola Ogunsemi et al [20] introduce a joint optimization problem (JAPTSP) combining JAP and TSP, employing NSGALP, MCRGALP, and SEQUENTIAL algorithms by investigating the linkages between two classical problems: job assignment problem and traveling salesman problem of a service chain system where service personnel performs tasks at different locations.. Results demonstrate NSGALP's superior performance, while MCRGALP shows balanced decision-making. Future research should focus on unbiased performance metrics and exploring algorithmic properties to balance computational time and solution quality.

D. Anuradha, M. Jayalakshmi and K. Kavitha [24] introduced One-to-One fixed method for obtaining an optimal solution and solving solid assignment problems in manufacturing logistics. The proposed method guides the decision-making process in a simple and efficient way to guide the decision-making process in a simple and efficient way.

Sudradjat Supian et al [27] proposed diverse approaches to tackle assignment problems, such as Sasaki's new approach, Maxon and Bhadury's consideration of repetitive tasks, and Bogomolnaia and Moulin's solution for random assignment. This research specifically focuses on optimizing personnel assignment using the Hungarian method, illustrated through a case study at the central post office in Bandung, including sensitivity analysis to maintain optimal assignments despite data changes. By utilizing the Hungarian Method to achieve optimal assignments and conducting sensitivity analysis to ensure robustness to data changes.

Jungwoo Lee et al [19] proposes a deep neural network (DNN) model to efficiently solve the multi-job assignment problem in a multi-agent system, addressing the complexity of combined vehicle routing problems. By leveraging a large training dataset generated using the planning domain definition language (PDDL) and preprocessed optimal solutions and the DNN achieves consistent performance regardless of parameter variations, significantly reducing execution time compared to traditional methods.

Chittaranjan Mallicka et al [6] discusses the Course and Lecturer Assignment Problem Solver (CLAPS) using the Hungarian method in an educational institution to optimize course assignments. It emphasizes the application of Operations Research techniques as powerful decision-making tools for administrators in educational institutions.

Syakinah Faudzi et al [25] offers an extensive review of assignment problems within the education sector, categorizing them into timetabling and allocation problems. It delves into the nuances of each problem type, including examination, course, and school timetabling, as well as student-project, new student, and space allocation and exploring various solution methodologies, emphasizing the importance of selecting appropriate approaches to attain optimal or near-optimal solutions, with heuristic and Metaheuristic methods being predominant due to their effectiveness in addressing the complexity of real-world scenarios.

M. Zhong et al. [40] introduce a Parallel Optimization Method for train scheduling and shunting at complex high-speed railway stations. They develop a Track-based Resource Network (TRN) model to enhance scheduling precision and efficiency. The study integrates Lagrangian Relaxation (LR) and the Alternating Direction Method of Multipliers (ADMM) to optimize station operations and resolve train conflicts. A parallel computing strategy improves computational efficiency, making the approach scalable for large stations. Real-world case studies demonstrate that the method generates high-quality, conflict-free schedules while significantly reducing computational time compared to traditional methods. The findings contribute to enhancing rail network efficiency and station capacity utilization.

Z. Liao et al. [41] propose a Multiobjective Optimization Approach for estimating railway network capacity utilization while considering mixed train routes and stopping patterns. They employ a time-space network model combined with the ε-constraint method to generate Pareto-optimal saturated timetables, which balance service quality and operational efficiency. The study analyzes how different train scheduling strategies affect network capacity and passenger experience. The proposed approach provides a more comprehensive estimation of railway capacity than traditional scalar-based methods. A case study on the Zhengzhou high-speed and

intercity rail network highlights the trade-offs between capacity maximization and service reliability, helping railway planners optimize network efficiency.

S. Vafaei and M. Yaghini [42] developed a machine learning-based model for predicting train arrival and departure times at stations. They analyze Artificial Neural Networks (ANN), Random Forest (RF), Gradient Boosting (GB), and XGBoost, selecting the best model for each station to improve real-time scheduling accuracy. The study focuses on Tehran-Mashhad railway operations, utilizing three years of train operation data. The proposed models significantly enhance the precision of delay predictions, aiding railway traffic control centers in rescheduling operations more effectively. This research contributes to the growing field of AI-driven railway optimization, offering a data-driven solution to reduce delays and improve passenger experience.

A. Giulianetti et al. [43] conducted a comparative analysis of train departure strategies in container shipments using Discrete-Event Simulation (DES). The study evaluates different departure scheduling policies to optimize container dwell time, train utilization, and terminal efficiency. Using real-world data from the Genoa Port Terminal, the research identifies how different departure strategies impact train load factors and departure frequencies. The findings emphasize the need for data-driven scheduling decisions to improve rail freight efficiency and reduce terminal congestion. The study offers practical insights for logistics operators and policymakers seeking to enhance rail-based container transportation.

M. Botte et al. [39] propose an Optimal Layover Time Allocation Method in smart DC railway metro traction systems to improve energy efficiency. The study introduces a two-step optimization framework integrating Optimal Power Flow (OPF) control to regulate train voltage and maximize regenerative braking (RB) energy recovery. The approach optimally distributes layover times among stops, reducing overall energy consumption. A case study on Naples Metro Line 1 demonstrates significant energy savings using a centralized control strategy over conventional methods. The research advances sustainable railway operations by enhancing power management strategies and minimizing energy losses in metro systems.

Table 1: Summary of literature review

SN	Author	Year	Topic	Methodology	Gaps
1.	S. Vafaei and M. Yaghini [42]	2024	Online prediction of arrival and departure times in each station for passenger trains using machine learning methods	Machine learning models: ANN, RFR, GBR, EGBR, etc	Study's focus on a single train route and five main stations limits.
2.	A. Giulianetti et al. [43]	2024	Comparative Analysis of Train Departure Strategies in a Container Shipment	Simulation modeling, performance metrics, and scenario analysis	lacks real-world validation, multimodal integration, dynamic scheduling, sustainability focus, and large-scale network complexity
3.	Z. Liao et al. [41]	2024	Estimating the Railway Network Capacity Utilization with Mixed Train Routes and Stopping Patterns: A Multiobjective Optimization Approach	Lagrangian relaxation, FCFS passenger assignment, and heuristic scheduling	lacks real-world validation, dynamic demand adaptability, multimodal integration, sustainability considerations, and scalability assessment for large networks
4.	M. Zhong et al. [40]	2024	Parallel optimization method of train scheduling and shunting at complex high-	TRN-based modeling, OSM, LR, ADMM, and parallel computing	Lacks real-time adaptability, high computational complexity, no energy efficiency, limited multimodal integration, and rigid

			speed railway stations		scheduling rules
5.	M. Botte et al. [39]	2024	Optimal Allocation of Layover Time in a Smart DC Railway Metro Traction System	integrating OPF-based control to maximize regenerative braking and energy efficiency	real-time adaptability, scalability analysis, passenger impact assessment, multimodal integration, and cost-benefit evaluation
6.	Chittaranjan Mallick et al [33]	2023	Cost minimization of airline crew scheduling problem using assignment technique	pairing routes to minimize crew costs	The current methods lack sufficient heuristics to effectively manage large-scale and dynamic scheduling scenarios.
7.	Felix Eduardo Bueno-Pascual et al [34]	2023	A vehicle assignment problem to improve logistics operations in a Mexican freight transport company	Employs factor analysis and ANOVA	This models do not adequately address the integration of different types of vehicles and their specific cost implications.
8.	Souhail dhouib [35]	2023	Novel optimization method for unbalanced assignment problems with multiple jobs: the dhouib-Matrix-AP2.	Proposed DM-AP2 algorithm	The paper lacks an exploration of dynamic scenarios and scalability issues, limiting its applicability to real-world situations where tasks and resources frequently change.

9.	Humayra Dil Afroz and Jyoti Dass [36]	2023	An alternative proposed system for solving assignment problems.	Proposed new method	Current approaches do not adequately address complex problems in their performance evaluations.
10.	V. Meczko et al [4]	2023	Optimization of operator-machine assignment problem using excel solver.	Optimization of operator-machine assignment problem using excel solver.	This research does not sufficiently explore the application of linear programming to certain problem domains.
11.	Farzana Afrin Mim et al [5]	2022	New approach to solve assignment problems with branch and bound algorithm.	New Approach to Solve Assignment Problems with Branch and Bound Algorithm.	There is no detailed comparative analysis with other state-of-the-art algorithms, which could provide insights into the advantages and disadvantages of the proposed approach.
12.	Kah Yong Tiong et al [7]	2023	A review of data-driven approaches to predict train delays.	Regression, ML, Neural Network & hybrid method	This paper often lacks a comprehensive evaluation of models based on multiple criteria such as accuracy, explainability, and validity.
13.	Mehmet Sirin Artan and Ismail Sahin [8]	2022	Exploring pattern of train delay evolution and timetable robustness.	homogeneous and non-homogeneous Markov chain models	There is a need for research to incorporate more granular data and develop models that can adapt to varying operational conditions.

14.	Eva Konig [10]	2020	A review of railway delay management.	deterministic, stochastic, and heuristic models	There is a significant lack of integrated models that consider both passenger and train perspectives in delay management, alongside limited studies on stochastic inputs and the interconnections with other operational problems.
15.	Ping Huang et al [13]	2020	A deep learning approaches for multi-attribute data: a study of train delay prediction in railway systems.	Conventional neural network & long short-term memory	Current approaches often overlook the simultaneous consideration of spatial and temporal autocorrelations.
16.	Ping Huang et al [21]	2020	A hybrid model to improve the train running time prediction ability during high-speed railway distribution.	Hybrid model of support vector regression and Kalman filter	There is a need to explore the application of machine learning models, such as random forest, k-nearest neighbor, and artificial neural networks (ANN), in this domain.
17.	Yuxiang Yang et al [32]	2019	Statistical delay distribution analysis on high-speed railway trains.	Kolmogorov–Smirnov (K–S) test.	There is a need for studies that focus on individual routes or lines to understand their unique characteristics and impacts.

3 RESEARCH GAPS

From the above literature review, the following research gaps have been identified:

- **3.1** Limited heuristics for large-scale and dynamic scheduling scenarios, and insufficient scalability in current approaches [33], [35], [36].
- **3.2** Inadequate integration of diverse factors, such as vehicle types, cost implications, and complex problem evaluations [34], [36].
- **3.3** Limited application and comparative analysis of machine learning models and optimization techniques [4], [5], [21].
- **3.4** Lack of comprehensive evaluations based on multiple criteria and real-time operational conditions [7], [8], [10].
- **3.5** Absence of holistic and integrated models considering both passenger and train perspectives, alongside spatio-temporal factors [10], [13].
- **3.6** Limited focus on route-specific characteristics and scalability across different contexts [32], [33].

4 PROBLEM STATEMENT

Train punctuality has long been a subject of concern and debate in railway systems worldwide. Punctuality refers to the ability of trains to adhere to their scheduled arrival and departure times. Key factors affecting punctuality include traffic management, rising passenger and freight demands, weather conditions, infrastructure issues, network congestion, and various operational challenges.

To address these issues, optimization techniques can be applied to minimize delays and disruptions by creating more efficient schedules that consider potential problems such as maintenance, unexpected incidents, or congestion. Enhancing punctuality through optimization not only improves the reliability of train services but also increases their appeal to passengers and freight shippers. The focus of this study, *"Optimization of Train Scheduling Delays in Indian Railways"* aims to improve punctuality and reduce delays in train operations.

5 RESEARCH OBJECTIVES

5.1 To study and analyze the assignment optimization problem and investigate the root causes of train delays in Indian Railways.

5.2 To perform a computational analysis of heuristic and metaheuristic assignment optimization algorithms, evaluating their advantages, limitations, and areas of application.

5.3 To develop an improved algorithm for solving assignment problems more efficiently, enhancing the performance of existing methods.

5.4 To propose a hybrid optimization approach for minimizing train scheduling delays, efficient use of layover periods, and improving infrastructure utilization.

5.5 To conduct a comparative analysis of train departure delays before and after implementing the proposed optimization strategies to evaluate their effectiveness.

6 RESEARCH METHODOLOGY

6.1 Study Collection of train punctuality data from Indian Railway: Collect comprehensive data on train punctuality, including scheduled and actual arrival/departure times, delay durations, and frequency of delays. Utilize sources such as railway databases and tracking systems. Consider contextual factors like weather and peak travel seasons to provide a complete understanding of punctuality issues.

6.2 Pre-processing and tabulation of punctuality data: Pre-process the collected data to ensure accuracy by removing duplicates, correcting inaccuracies, and filling in missing values. Normalize the dataset for consistency and organize it into structured tables categorized by train type, route, arrival time, departure time, etc. This structured format is essential for effective analysis and further processing.

6.3 Hybrid approach of existing Methods i.e. Hungarian algorithm, Greedy Method, Metaheuristic Algorithms, Machine Learning, etc: Integrate established optimization techniques like the Hungarian algorithm, greedy methods, metaheuristic algorithms, and machine learning to form a hybrid approach. Each method's strengths will be leveraged to address complex

scheduling and delay management issues, creating a comprehensive strategy tailored to improve train punctuality.

6.4 Apply a hybrid approach to improve the punctuality of trains: Implement the hybrid approach to optimize train schedules and resource allocations aimed at enhancing punctuality. Adjust schedules based on predicted delays and manage resources dynamically using real-time data inputs. Continuous monitoring during implementation will ensure the strategy effectively reduces delays and improves overall service reliability.

6.5 Performance evaluation of outcome: Evaluate the effectiveness of the hybrid approach by analyzing performance metrics such as punctuality rates, average delays, and service reliability. Compare data before and after implementation to measure improvement. Utilize statistical analyses to assess results, identifying successes and areas needing further enhancement.

7 EXPECTED OUTCOME OF THE RESEARCH

This research is expected to result in several significant improvements in railway operations through the application of advanced optimization techniques. Firstly, a reduction in train departure delays is anticipated, leading to improved schedule adherence and increased passenger satisfaction. By optimizing layover periods and streamlining the boarding process, overall operational efficiency will be enhanced, allowing for quicker turnaround times and reduced idle periods at stations. These improvements will contribute to a more seamless and reliable railway experience for passengers.

Additionally, the study aims to develop an improved optimization method for assignment problems, enhancing the computational efficiency and accuracy of existing heuristic and metaheuristic algorithms. A hybrid approach will be introduced to optimize train scheduling and resource allocation, ensuring better utilization of railway infrastructure without requiring significant additional investments. This strategic deployment of trains is expected to maximize capacity, minimize operational inefficiencies, and improve service reliability.

Furthermore, a comparative analysis of railway operations before and after

implementing optimization strategies will provide measurable insights into the effectiveness of the proposed approach. Quantifiable reductions in delays, improved train assignments, and better infrastructure utilization will demonstrate the practical benefits of optimization in real-world scenarios. These improvements have the potential to enhance the profitability of railway operations by attracting more passengers, optimizing freight transport, and reducing operational costs.

Ultimately, this research aims to contribute to the development of a more efficient, reliable, and profitable railway system. The findings will not only provide valuable theoretical insights into optimization algorithms but also offer practical applications that can be implemented to enhance railway performance, ensuring long-term sustainability and improved service quality.

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YASH KUMAR

DEVELOPING HYBRID OPTIMIZATION APPROACH FOR MINIMIZING TRAIN SCHEDULING DELAYS IN INDIAN RAIL...

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DEVELOPING HYBRID OPTIMIZATION APPROACH FOR MINIMIZING TRAIN SCHEDULING DELAYS IN INDIAN RAILWAYS

SHORT SYNOPSIS

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Abstract

An essential part of India's transportation infrastructure, Indian Railways, the country's fourth-largest railway network worldwide, promotes mass mobility, socio-economic development, and connectivity. It began as a 34-kilometer trip between Bori Bunder, Bombay and Thane in 1853, powered by three locomotives: Sindh, Sahib, and Sultan. Across 7,349 railway stations, Indian Railways currently runs approximately 22,593 trains that carry 24 million passengers and 203 million tonnes of freight per day. Even while IR brought in ₹2.39 Lakh Crore in income in FY 2022–2023, it still has a lot of issues in the current world, especially when it comes to train punctuality, which is a crucial indicator of operational effectiveness and passenger

happiness. Train punctuality was 94.17% in FY 2020–21 and dropped to 90.48% in FY 2021–22, indicating the need for more concentrated efforts in this area.

Numerous factors, such as network congestion, inadequate infrastructure, weather, and rising demand for passenger and freight services, have an impact on the railway system's punctuality. There are two types of delays that have a major impact on punctuality; primary delays and secondary delays. Direct causes like weather conditions, operational difficulties, or typical events like fires or accidents are the main causes of primary delays. As railway operations are interrelated and one delayed train can impact the scheduling of other trains, secondary delays arise as a result of primary delays.

Optimization techniques like Hungarian Algorithm, Two Phase Approach (TPA) Method, Jonker-Volganant Algorithm, First In First Out (FIFO) Algorithm, Linear Programming and Hybrid Approaches, etc are essential to increase productivity and decrease delays. Applications in engineering, finance, and operations, optimization is the process of determining the best way to solve a problem while meeting a set of constraints. By putting these strategies into practice, Indian Railways might improve operations and may improve the punctuality of trains, efficient use of infrastructure, meet the demands of its extensive passenger and freight network more effectively, and improve punctuality while cutting costs.

Keywords: Assignment Problem, Delay, Indian Railways, Optimization Techniques, Train Punctuality, Train Scheduling.

1 Description of Broad Area

1.1 Indian Railways

The Indian Railways (IR) operates the world's fourth-largest train network. It is vital for facilitating mass transit, connecting distant places, and contributing significantly to the country's socioeconomic development. IR was established in 1853. The first train traveled from Bori Bunder, Bombay to Thane, a distance of 34 kilometers. On April 16, 1853, it was powered by three locomotives named Sahib, Sultan, and Sindh, with thirteen cars. The Indian Railways operates 22,593 trains/day, carrying 24 million passengers and 203 million tons of freight. 7,349 railway stations operate under the authority of 70 railway divisions, with each station operating independently for train operations. In FY 2022-2023, the total expenditure and revenue were ₹2.37 and ₹2.39 lakh crore, respectively [28], [29]. The railway network, which serves as the backbone of India's transportation infrastructure, faces various issues today. Timely departures, effective station operations, and optimal resource utilization are essential elements that directly affect operational success and customer satisfaction.

1.2 Train punctuality

According to Indian Railways Annual Report & Accounts 2020-21 & 2021-22 [28], [29], train punctuality for the FY 2020-21 and FY 2021-22 was 94.17% and 90.48%, respectively. These figures are incredibly high and demonstrate Indian Railways' great priority for punctuality. In every railway system, there has been debate and worry about train punctuality. The ability of trains to arrive and depart on time is referred to as punctuality. The main elements influencing the railway system's punctuality include traffic management, increasing passenger and freight demands, weather, infrastructure problems, network congestion, and operational challenges [30].

1.3 Classification of Delay Factors in Railways System

A train is considered to be delayed when it departs from its starting point, travels later than planned, and arrives at its destination station later than expected. Any railway system's classification of delays is divided into various subcategories, although they can be essentially divided into two categories: primary delays and secondary delays.

1.3.1 Primary Delays

The term "primary delay" in railways refers to the initial delay caused by a variety of factors that impact a train's scheduled travel. These delays are the direct result of disturbances or issues that prohibit the train from departing or arriving on schedule. Some common reasons of main delays are:

- **Unusual Occurrence**: Cattle run over, accident, Fire, etc.
- **Environment factors**: Heavy Rain, Wind, Snow, Flood, Landslide, Earthquake, etc.
- **Operational Causes**: Crew issues, Vehicle Problems, Unscheduled maintenance due to failure, etc.
- **External Factors**: Obstruction of the track, Passenger issues, etc.

1.3.2 Secondary Delay

Secondary delays in railways arise as a result of main delays, in which one train's delay creates subsequent delays for other trains. These delays occur because railway operations are interrelated, with train movement and scheduling being interdependent. The following are some common causes of secondary delays:

- **Track Occupancy**: A delayed train occupying a section of track or a platform longer than scheduled can prevent other trains from accessing the same track or platform, causing them to wait.
- **Connection Delays**: Trains scheduled to connect with the delayed train must wait for its arrival to ensure passengers can transfer, leading to a cascade of delays.
- **Arrival and Departure Delay (Scheduling Conflicts)**: The initial delay disrupts the planned schedule, leading to a domino effect where subsequent trains cannot adhere to their allocated time slots.

1.4 Optimization Techniques

Optimization problems focus on determining the ideal value of an objective function while satisfying a set of predefined constraints. The objective function mathematically represents the goal of the optimization—whether it involves minimizing costs, maximizing efficiency, or enhancing performance. On the other hand, constraints define the requirements that must be met for the solution to be considered valid. Optimization techniques are widely applicable across various fields, including computer science, engineering, and finance. They play a critical role in industries by helping solve complex problems, maximize resource usage, and drive significant improvements in operations. These techniques can be applied to minimize production costs, optimize workflow processes, improve revenue generation, and ensure efficient time management. As a result, businesses can leverage optimization algorithms to improve decision-making and increase overall productivity.

- Finding the optimal value for an objective function that fulfills a given set of restraints is the focus of optimization problems.
- The constraints are the requirements that the solution must meet, while the objective function is the function that is being optimized.
- Engineering, finance, computer science, and many other disciplines are just a few examples of the various disciplines where optimization algorithms can be applied.
- They can be used to find solutions for cutting production costs, increasing revenues, speeding up work completion, efficient use of time and many more.

A specific type of optimization problem is the assignment problem, which is highly beneficial in areas like train scheduling. The assignment problem involves allocating a set of tasks to a set of resources in the most efficient manner possible. For instance, in train scheduling, the problem can be used to allocate trains to specific routes, tracks, or time slots. This ensures that the scheduling of trains is done optimally, minimizing costs, delays, or idle time while maximizing the efficient use of resources such as tracks and locomotives. The assignment problem can be formulated as a linear programming problem, where the goal is to determine the most optimal allocation of resources to tasks based on a given objective, such as minimizing costs or maximizing benefits. In the assignment problem, each agent (train) can only be assigned to one task (route or time slot), and each task can only be assigned to one agent. The aim is to find the assignment that best aligns agents with tasks while adhering to the cost or benefit function. Mathematically, this can be expressed using a bipartite graph, with two sets of nodes representing agents and tasks, respectively. The edges between the nodes signify the possible assignments, and each edge has an associated weight that represents the cost or benefit of that assignment. The goal is to find the optimal matching, where every agent is assigned to exactly one task, and the total cost is

minimized, or the total benefit is maximized. Various algorithms have been developed to solve the assignment problem efficiently. One of the most well-known is the Hungarian algorithm [6], which is widely used due to its effectiveness in finding optimal assignments. Other notable algorithms include the shortest path augmenting path algorithm, the Auction Method [38], and the Jonker-Volgenant algorithm [37], each offering different approaches to solve the problem under varying conditions. The assignment problem is applicable in many domains, from logistics and manufacturing to scheduling and resource allocation. For example, in logistics, it can be used to assign delivery vehicles to routes in a way that minimizes travel time or fuel consumption. In manufacturing, it helps assign tasks to machines to reduce production costs or completion time. In scheduling, it ensures that shifts are assigned to employees in a way that guarantees adequate coverage while minimizing labor costs. By addressing these complex scenarios, the assignment problem offers a powerful tool for optimizing decisions across a wide array of industries.

Over the recent years, to solve assignment problems sufficiently; Humayra Dil Afroz & Jyoti Das [1] proposed the basic structure of the Hungarian Algorithm but introduced specific modifications at each step. The steps involve adjusting the cost matrix, normalizing rows and columns, making assignments, checking optimality through line drawing, and iteratively refining the solution until an optimal assignment is achieved. This type of approach falls under the broader category of combinatorial optimization algorithms, and more specifically, it addresses the assignment problem. Farzana Afrin Min et al [3] proposed an approach that follows a heuristic method known as the ‘Assignment by Adjustment’ or ‘Row Minima Method’ for solving the assignment problem. The assignment problem involves finding the most cost-effective way to assign a set of jobs to a set of machines, workers, or resources. This approach is a heuristic because it relies on a simple and fast procedure for finding an assignment, but it does not guarantee optimality. It provides a feasible solution quickly, but the solution may not be the most cost-effective in all cases. R. Murugesan & T. Esakkiammal [22] proposed approach is a step-by-step process for solving an Assignment Problem, a type of combinatorial optimization problem. This method involves balancing the assignment table, constructing the Matrix of Opportunity Costs (MOC), making assignments, and iterating until all assignments are made. This approach follows a systematic procedure to find an optimal solution to an Assignment Problem, considering balancing, opportunity costs, and tie-breaking techniques. V. Meczko et al [2] proposed approach described involves using the Excel Solver for optimization, specifically for solving an operator-machine assignment problem. This is an example of a mathematical programming approach, specifically linear programming, where the goal is to optimize a linear objective function subject to certain linear constraints. Neha Rai et al [12], Humayra Dil Afroz et al [11] proposed approach is a heuristic method because it involves making decisions based on local information (e.g., considering the current row's zeros) rather than exhaustively exploring all possible assignments. It might not guarantee the globally optimal solution, but it provides a reasonable solution in a more computationally efficient manner. This algorithm seems similar to some heuristics used in solving the Assignment Problem, and it falls under the category of constructive heuristics. Constructive heuristics build a solution step by step, making locally optimal decisions at each stage.

2 Literature Review

The assignment problem is a classic optimization scenario in operations research and combinatorial optimization. It involves finding the most cost-effective assignment of a set of tasks to a set of resources. This problem arises in various real-world applications such as workforce management, project scheduling, and transportation planning. In its simplest form, the assignment problem can be framed as follows: Given a set of tasks and a set of resources, each with associated costs or weights, the goal is to find the optimal assignment that minimizes the total cost. The problem is often represented as a cost matrix, where each element represents the cost of assigning a particular task to a specific resource. Various approaches have been created over time to address this issue, each with its own set of strengths and weaknesses. Some are as follows:

2.1 Hungarian Method

The Hungarian method, introduced by Kuhn in 1955 [6], is one of the most popular methods for addressing the assignment problem. It effectively determines the optimal solution in polynomial time, making it appropriate for small to medium-sized problems. The Hungarian technique divides the problem into a succession of simpler sub-problems by combining matrix reduction and augmenting routes, eventually leading to the optimal assignment. While incredibly efficient, it may face scaling challenges with huge problem instances.

2.2 Linear Programming

Linear programming (LP) techniques can be used to solve the assignment problem by transforming it into an LP problem and employing optimization solvers. LP-based techniques provide flexibility in dealing with various sorts of cost matrices and limitations. They can provide optimal answers and handle increasingly complex variations of the assignment problem. However, solving large-scale LPs can be computationally demanding and may not be as efficient as specialized assignment techniques for smaller instances [9].

2.3 Network Flow Algorithms

Network flow algorithms, such as the minimum cost flow algorithm, can be used to solve the assignment problem by representing it as a flow network. While capable of discovering optimal solutions, some methods may be more sophisticated than other algorithms. Network flow techniques are very useful when dealing with extra limitations or expanding the assignment problem to more complex circumstances [14].

2.4 Heuristic and Greedy Methods

Heuristic methods, such as the "row and column scanning" approach, offer quickly and approximate answers to the assignment problem. These methods are useful for creating initial solutions, particularly in larger scenarios where optimality is harder to achieve. Greedy algorithms that iteratively make locally optimum assignments can yield good answers, but may not ensure global optimality [15].

2.5 Branch and Bound

The branch and bind technique investigate the solution space by recursively splitting it into smaller sub-problems and restricting the search to find the best assignment. While it ensures optimality, its effectiveness is dependent on the branching strategy

and the quality of the bounding approaches. It can be effective in circumstances where optimality is critical and other methods may fall short [3].

2.6 Metaheuristic Algorithms

Metaheuristic techniques, such as genetic algorithms, simulated annealing, and particle swarm optimization, provide a balance between solution quality and computing time. These techniques are valuable in difficult assignment situations where typical methods may fail. However, their convergence to optimal solutions is not assured and fine-tuning is frequently required [17], [25], [31].

2.7 Hybrid Approaches

Hybrid methods incorporate aspects from many techniques to maximize their strengths. For example, combining the Hungarian technique with local search strategies can boost solution quality and efficiency. These approaches seek to capitalize on the advantages of various methodologies while limiting their downsides [16].

Finally, there are several approaches for handling the assignment problem, each with pros and disadvantages. The approach chosen is determined by several parameters, including issue size, cost matrix structure, available computer resources, and the desired balance of solution quality and calculation time. Researchers continue to develop hybrid approaches and apply improved optimization techniques to effectively handle larger and more complicated assignment situations. To solve the real life assignment problems, in recent years, many efforts are made with discrete type of assignment problems.

Yani Iriania and Tendy Andrian [23] introduce the use of the Hungarian assignment method to optimize employee assignments in the sewing line area to address the issue of delays in work completion and increased overtime due to the company's current assignment practices, resulting in a significant reduction in work completion time from 43.3 hours to 35 hours.

Zsolt Ercsey and Zoltán Kovács [18] address the problem of allocating work assignments to employees within a given time horizon, considering varying manpower demands and compliance with labor standards and regulations, formulate a corresponding Mixed Integer Linear Programming (MILP) mathematical programming model in a simple scenario where there is only one position for labor, as well as in a general case where there are multiple positions with different skill requirements, The models offer a fast and effective method for human resource managers to optimize labor scheduling and support decision-making in workforce allocation.

Trupti A Thakre et al [26] explore how fuzzy assignment problems address the limitations of classical approaches, offering a solution for the placement of candidates across different designations in the Life Insurance Corporation sector, employing various methodologies for comparison and analysis. The utilization of the magnitude ranking method and various solution techniques like the Hungarian method, Matrix One's assignment method, and direct method for the fuzzy assignment problem highlights its effectiveness in efficiently placing candidates for different posts in the Life Insurance Corporation, ensuring optimal placements with consistent outcomes.

Akinola Ogunsemi et al [20] introduce a joint optimization problem (JAPTSP) combining JAP and TSP, employing NSGALP, MCRGALP, and SEQUENTIAL algorithms by investigating the linkages between two classical problems: job assignment problem and traveling salesman problem of a service chain system where service personnel performs tasks at different locations.. Results demonstrate NSGALP's superior performance, while MCRGALP shows balanced decision-making. Future research should focus on unbiased performance metrics and exploring algorithmic properties to balance computational time and solution quality.

D. Anuradha, M. Jayalakshmi and K. Kavitha [24] introduced One-to-One fixed method for obtaining an optimal solution and solving solid assignment problems in manufacturing logistics. The proposed method guides the decision-making process in a simple and efficient way to guide the decision-making process in a simple and efficient way.

Sudradjat Supian et al [27] proposed diverse approaches to tackle assignment problems, such as Sasaki's new approach, Maxon and Bhadury's consideration of repetitive tasks, and Bogomolnaia and Moulin's solution for random assignment. This research specifically focuses on optimizing personnel assignment using the Hungarian method, illustrated through a case study at the central post office in Bandung, including sensitivity analysis to maintain optimal assignments despite data changes. By utilizing the Hungarian Method to achieve optimal assignments and conducting sensitivity analysis to ensure robustness to data changes.

Jungwoo Lee et al [19] proposes a deep neural network (DNN) model to efficiently solve the multi-job assignment problem in a multi-agent system, addressing the complexity of combined vehicle routing problems. By leveraging a large training dataset generated using the planning domain definition language (PDDL) and preprocessed optimal solutions and the DNN achieves consistent performance regardless of parameter variations, significantly reducing execution time compared to traditional methods.
Chittaranjan Mallicka et al [6] discusses the Course and Lecturer Assignment Problem Solver (CLAPS) using the Hungarian method in an educational institution to optimize course assignments. It emphasizes the application of Operations Research techniques as powerful decision-making tools for administrators in educational institutions.

Syakinah Faudzi et al [25] offers an extensive review of assignment problems within the education sector, categorizing them into timetabling and allocation problems. It delves into the nuances of each problem type, including examination, course, and school timetabling, as well as student-project, new student, and space allocation and exploring various solution methodologies, emphasizing the importance of selecting appropriate approaches to attain optimal or near-optimal solutions, with heuristic and Metaheuristic methods being predominant due to their effectiveness in addressing the complexity of real-world scenarios.

M. Zhong et al. [40] introduce a Parallel Optimization Method for train scheduling and shunting at complex high-speed railway stations. They develop a Track-based Resource Network (TRN) model to enhance scheduling precision and efficiency. The

study integrates Lagrangian Relaxation (LR) and the Alternating Direction Method of Multipliers (ADMM) to optimize station operations and resolve train conflicts. A parallel computing strategy improves computational efficiency, making the approach scalable for large stations. Real-world case studies demonstrate that the method generates high-quality, conflict-free schedules while significantly reducing computational time compared to traditional methods. The findings contribute to enhancing rail network efficiency and station capacity utilization.

Z. Liao et al. [41] propose a Multiobjective Optimization Approach for estimating railway network capacity utilization while considering mixed train routes and stopping patterns. They employ a time-space network model combined with the ε-constraint method to generate Pareto-optimal saturated timetables, which balance service quality and operational efficiency. The study analyzes how different train scheduling strategies affect network capacity and passenger experience. The proposed approach provides a more comprehensive estimation of railway capacity than traditional scalar-based methods. A case study on the Zhengzhou high-speed and intercity rail network highlights the trade-offs between capacity maximization and service reliability, helping railway planners optimize network efficiency.

S. Vafaei and M. Yaghini [42] developed a machine learning-based model for predicting train arrival and departure times at stations. They analyze Artificial Neural Networks (ANN), Random Forest (RF), Gradient Boosting (GB), and XGBoost, selecting the best model for each station to improve real-time scheduling accuracy. The study focuses on Tehran-Mashhad railway operations, utilizing three years of train operation data. The proposed models significantly enhance the precision of delay predictions, aiding railway traffic control centers in rescheduling operations more effectively. This research contributes to the growing field of AI-driven railway optimization, offering a data-driven solution to reduce delays and improve passenger experience.

A. Giulianetti et al. [43] conducted a comparative analysis of train departure strategies in container shipments using Discrete-Event Simulation (DES). The study evaluates different departure scheduling policies to optimize container dwell time, train utilization, and terminal efficiency. Using real-world data from the Genoa Port Terminal, the research identifies how different departure strategies impact train load factors and departure frequencies. The findings emphasize the need for data-driven scheduling decisions to improve rail freight efficiency and reduce terminal congestion. The study offers practical insights for logistics operators and policymakers seeking to enhance rail-based container transportation.

M. Botte et al. [39] propose an Optimal Layover Time Allocation Method in smart DC railway metro traction systems to improve energy efficiency. The study introduces a two-step optimization framework integrating Optimal Power Flow (OPF) control to regulate train voltage and maximize regenerative braking (RB) energy recovery. The approach optimally distributes layover times among stops, reducing overall energy consumption. A case study on Naples Metro Line 1 demonstrates significant energy savings using a centralized control strategy over conventional methods. The research advances sustainable railway operations by enhancing power management strategies and minimizing energy losses in metro systems.

Table 1: Summary of literature review

SN	Author	Year	Topic	Methodology	Gaps
1.	S. Vafaei and M. Yaghini [42]	2024	Online prediction of arrival and departure times in each station for passenger trains using machine learning methods	Machine learning models: ANN, RFR, GBR, EGBR, etc	Study's focus on a single train route and five main stations limits.
2.	A. Giulianetti et al. [43]	2024	Comparative Analysis of Train Departure Strategies in a Container Shipment	Simulation modeling, performance metrics, and scenario analysis	lacks real-world validation, multimodal integration, dynamic scheduling, sustainability focus, and large-scale network complexity
3.	Z. Liao et al. [41]	2024	Estimating the Railway Network Capacity Utilization with Mixed Train Routes and Stopping Patterns: A Multiobjective Optimization Approach	Lagrangian relaxation, FCFS passenger assignment, and heuristic scheduling	lacks real-world validation, dynamic demand adaptability, multimodal integration, sustainability considerations, and scalability assessment for large networks
4.	M. Zhong et al. [40]	2024	Parallel optimization method of train scheduling and shunting at complex high-speed railway stations	TRN-based modeling, OSM, LR, ADMM, and parallel computing	Lacks real-time adaptability, high computational complexity, no energy efficiency, limited multimodal integration, and rigid scheduling rules
5.	M. Botte et al. [39]	2024	Optimal Allocation of Layover Time in a Smart DC	integrating OPF-based control to maximize regenerative	real-time adaptability, scalability analysis, passenger impact

			Railway Metro Traction System	braking and energy efficiency	assessment, multimodal integration, and cost-benefit evaluation
6.	Chittaranjan Mallick et al [33]	2023	Cost minimization of airline crew scheduling problem using assignment technique	pairing routes to minimize crew costs	The current methods lack sufficient heuristics to effectively manage large-scale and dynamic scheduling scenarios.
7.	Felix Eduardo Bueno-Pascual et al [34]	2023	A vehicle assignment problem to improve logistics operations in a Mexican freight transport company	Employs factor analysis and ANOVA	This models do not adequately address the integration of different types of vehicles and their specific cost implications.
8.	Souhail dhouib [35]	2023	Novel optimization method for unbalanced assignment problems with multiple jobs: the dhouib-Matrix-AP2.	Proposed DM-AP2 algorithm	The paper lacks an exploration of dynamic scenarios and scalability issues, limiting its applicability to real-world situations where tasks and resources frequently change.
9.	Humayra Dil Afroz and Jyoti Dass [36]	2023	An alternative proposed system for solving assignment problems.	Proposed new method	Current approaches do not adequately address complex problems in their performance evaluations.
10.	V. Meczko et al [4]	2023	Optimization of operator-machine assignment problem using excel solver.	Optimization of operator-machine assignment problem using excel solver.	This research does not sufficiently explore the application of linear programming to certain problem domains.
11.	Farzana Afrin Mim	2022	New approach to solve	New Approach to Solve	There is no detailed

	et al [5]		assignment problems with branch and bound algorithm.	Assignment Problems with Branch and Bound Algorithm.	comparative analysis with other state-of-the-art algorithms, which could provide insights into the advantages and disadvantages of the proposed approach.
12.	Kah Yong Tiong et al [7]	2023	A review of data-driven approaches to predict train delays.	Regression, ML, Neural Network & hybrid method	This paper often lacks a comprehensive evaluation of models based on multiple criteria such as accuracy, explainability, and validity.
13.	Mehmet Sirin Artan and Ismail Sahin [8]	2022	Exploring pattern of train delay evolution and timetable robustness.	homogeneous and non-homogeneous Markov chain models	There is a need for research to incorporate more granular data and develop models that can adapt to varying operational conditions.
14.	Eva Konig [10]	2020	A review of railway delay management.	deterministic, stochastic, and heuristic models	There is a significant lack of integrated models that consider both passenger and train perspectives in delay management, alongside limited studies on stochastic inputs and the interconnections with other operational problems.
15.	Ping Huang et al [13]	2020	A deep learning approaches for multi-attribute data: a study of train delay prediction in	Conventional neural network & long short-term memory	Current approaches often overlook the simultaneous consideration of spatial and temporal autocorrelations.

			railway systems.		
16.	Ping Huang et al [21]	2020	A hybrid model to improve the train running time prediction ability during high-speed railway distribution.	Hybrid model of support vector regression and Kalman filter	There is a need to explore the application of machine learning models, such as random forest, k-nearest neighbor, and artificial neural networks (ANN), in this domain.
17.	Yuxiang Yang et al [32]	2019	Statistical delay distribution analysis on high-speed railway trains.	Kolmogorov–Smirnov (K–S) test.	There is a need for studies that focus on individual routes or lines to understand their unique characteristics and impacts.

3 Research Gaps

From the above literature review, the following research gaps have been identified:

3.1 Limited heuristics for large-scale and dynamic scheduling scenarios, and insufficient scalability in current approaches [33], [35], [36].

3.2 Inadequate integration of diverse factors, such as vehicle types, cost implications, and complex problem evaluations [34], [36].

3.3 Limited application and comparative analysis of machine learning models and optimization techniques [4], [5], [21].

3.4 Lack of comprehensive evaluations based on multiple criteria and real-time operational conditions [7], [8], [10].

3.5 Absence of holistic and integrated models considering both passenger and train perspectives, alongside spatio-temporal factors [10], [13].

3.6 Limited focus on route-specific characteristics and scalability across different contexts [32], [33].

4 PROBLEM STATEMENT

Train punctuality has long been a subject of concern and debate in railway systems worldwide. Punctuality refers to the ability of trains to adhere to their scheduled arrival and departure times. Key factors affecting punctuality include traffic management, rising passenger and freight demands, weather conditions, infrastructure issues, network congestion, and various operational challenges.

To address these issues, optimization techniques can be applied to minimize delays and disruptions by creating more efficient schedules that consider potential problems such as maintenance, unexpected incidents, or congestion. Enhancing punctuality through optimization not only improves the reliability of train services but also increases their appeal to passengers and freight shippers. The focus of this study, *"Optimization of Train Scheduling Delays in Indian Railways"* aims to improve punctuality and reduce delays in train operations.

5 Research Objectives

5.1 To study and analyze the assignment optimization problem and investigate the root causes of train delays in Indian Railways.

5.2 To perform a computational analysis of heuristic and metaheuristic assignment optimization algorithms, evaluating their advantages, limitations, and areas of application.

5.3 To develop an improved algorithm for solving assignment problems more efficiently, enhancing the performance of existing methods.

5.4 To propose a hybrid optimization approach for minimizing train scheduling delays, efficient use of layover periods, and improving infrastructure utilization.

5.5 To conduct a comparative analysis of train departure delays before and after implementing the proposed optimization strategies to evaluate their effectiveness.

6 Research Methodology

6.1 Study Collection of train punctuality data from Indian Railway: Collect comprehensive data on train punctuality, including scheduled and actual arrival/departure times, delay durations, and frequency of delays. Utilize sources such as railway databases and tracking systems. Consider contextual factors like

weather and peak travel seasons to provide a complete understanding of punctuality issues.

6.2 Pre-processing and tabulation of punctuality data: Pre-process the collected data to ensure accuracy by removing duplicates, correcting inaccuracies, and filling in missing values. Normalize the dataset for consistency and organize it into structured tables categorized by train type, route, arrival time, departure time, etc. This structured format is essential for effective analysis and further processing.

6.3 Hybrid approach of existing Methods i.e. Hungarian algorithm, Greedy Method, Metaheuristic Algorithms, Machine Learning, etc: Integrate established optimization techniques like the Hungarian algorithm, greedy methods, metaheuristic algorithms, and machine learning to form a hybrid approach. Each method's strengths will be leveraged to address complex scheduling and delay management issues, creating a comprehensive strategy tailored to improve train punctuality.

6.4 Apply a hybrid approach to improve the punctuality of trains: Implement the hybrid approach to optimize train schedules and resource allocations aimed at enhancing punctuality. Adjust schedules based on predicted delays and manage resources dynamically using real-time data inputs. Continuous monitoring during implementation will ensure the strategy effectively reduces delays and improves overall service reliability.

6.5 Performance evaluation of outcome: Evaluate the effectiveness of the hybrid approach by analyzing performance metrics such as punctuality rates, average delays, and service reliability. Compare data before and after implementation to measure improvement. Utilize statistical analyses to assess results, identifying successes and areas needing further enhancement.

7 Expected Outcome of the Research

This research is expected to result in several significant improvements in railway operations through the application of advanced optimization techniques. Firstly, a reduction in train departure delays is anticipated, leading to improved schedule adherence and increased passenger satisfaction. By optimizing layover periods and streamlining the boarding process, overall operational efficiency will be enhanced, allowing for quicker turnaround times and reduced idle periods at stations. These improvements will contribute to a more seamless and reliable railway experience for passengers.

Additionally, the study aims to develop an improved optimization method for assignment problems, enhancing the computational efficiency and accuracy of existing heuristic and metaheuristic algorithms. A hybrid approach will be introduced to optimize train scheduling and resource allocation, ensuring better utilization of railway infrastructure without requiring significant additional investments. This strategic deployment of trains is expected to maximize capacity, minimize operational inefficiencies, and improve service reliability.

Furthermore, a comparative analysis of railway operations before and after implementing optimization strategies will provide measurable insights into the effectiveness of the proposed approach. Quantifiable reductions in delays, improved train assignments, and better infrastructure utilization will demonstrate the practical benefits of optimization in real-world scenarios. These improvements have the

potential to enhance the profitability of railway operations by attracting more passengers, optimizing freight transport, and reducing operational costs.

Ultimately, this research aims to contribute to the development of a more efficient, reliable, and profitable railway system. The findings will not only provide valuable theoretical insights into optimization algorithms but also offer practical applications that can be implemented to enhance railway performance, ensuring long-term sustainability and improved service quality.

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